

UNCLASSIFIED

AD NUMBER

AD465037

LIMITATION CHANGES

TO:

Approved for public release; distribution is unlimited.

FROM:

Distribution authorized to U.S. Gov't. agencies and their contractors;  
Administrative/Operational Use; MAR 1965. Other requests shall be referred to Department of the Air Force, Attn: Public Affairs Office, Washington, DC 20330.

AUTHORITY

USAF ltr, 8 Mar 1972

THIS PAGE IS UNCLASSIFIED

465037



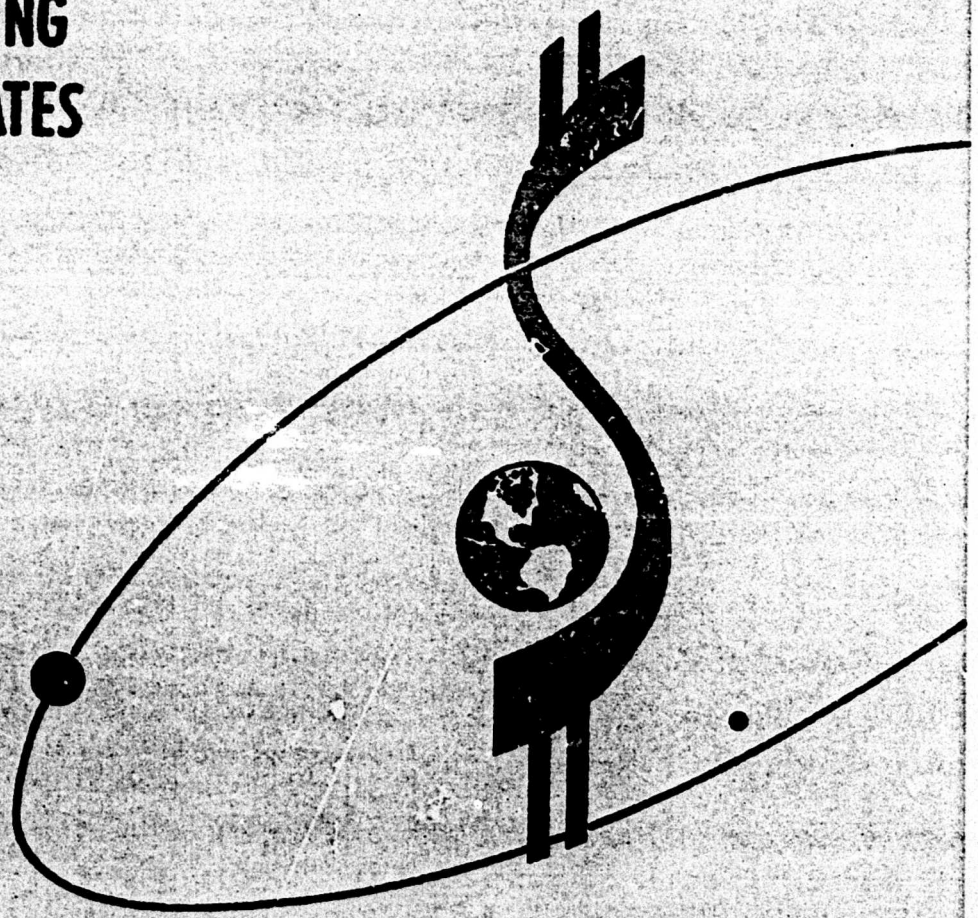
ANALYTIC SERVICES INC.

AM 65-2

CATALOGED BY: DDC  
AS AD M3

# A SURVEY OF TECHNIQUES FOR IMPROVING COST ESTIMATES OF FUTURE WEAPON SYSTEMS

R. D. CARTER  
March 1965



DDC  
JUN 2 1965

NOTICE: When government or other drawings, specifications or other data are used for any purpose other than in connection with a definitely related government procurement operation, the U. S. Government thereby incurs no responsibility, nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.

ANSER MEMORANDUM

AM 65-2

A SURVEY OF TECHNIQUES FOR IMPROVING COST  
ESTIMATES OF FUTURE WEAPON SYSTEMS

R. D. Carter

March 1965

*This document presents results of work sponsored by the Directorate of Development Plans, DCS Research and Development, Headquarters United States Air Force, under Contract AF 49(638)-1259. These results do not necessarily represent the official opinion or policy of the United States Air Force.*

*This document is a modification of a thesis submitted to the Faculty of the School of Engineering and Applied Science of The George Washington University in partial satisfaction of the requirements for the degree of Master of Engineering Administration.*

Analytic Services Inc.  
5613 Leesburg Pike, Falls Church, Virginia 22041

## A SURVEY OF TECHNIQUES FOR IMPROVING COST ESTIMATES OF FUTURE WEAPON SYSTEMS

### SUMMARY

The incongruity between estimated and actual costs of today's weapon systems indicates a need for cost estimates which more accurately predict the cost of future weapon systems. Estimates made near the beginning of a development program are particularly unreliable. For example, the cost of developing 11 existing weapon systems was as much as seven times the amount originally estimated. A study of the development and production costs of 33 weapon systems showed that the original cost estimates were 180 to 220 percent too low, on the average, even after price-level and cost-quantity adjustments were made. The problem becomes acute when cost estimates are requested for Air Force weapon systems expected to become operational as much as 10 years in the future.

Causes for cost overruns include technical complexity, technical obsolescence, schedule slippages, and contractor optimism. Frequently, a cost estimate is inadequate because it does not include all the necessary elements of total

system cost. However, by far the greatest cause of cost overruns is requirements uncertainty. Sudden and unpredictable changes in technology, enemy plans, and U.S. defense policies can change the requirement for a weapon system drastically, or even result in the program's cancellation. A change in operational concept could significantly affect installations and personnel costs. The other major cause of cost overruns is technological uncertainty. The size of cost overruns is directly related to the degree of technological advance sought. For example, missile programs requiring ambitious advances in state-of-the-art have much larger cost overruns than do cargo and tanker aircraft programs which require relatively modest innovations.

An adjustment factor can be applied to cost estimates in an attempt to account for technological and requirements uncertainties. The adjustment factor is the ratio between actual and estimated costs of completed weapon systems requiring advances in technology which are comparable with those of the new system. Adjustment factors must be applied to all elements of the total system cost, a long and tedious process. Adjustment factors might account for technological

uncertainty, but technical breakthroughs, enemy capabilities, and new operational concepts cannot be accounted for by applying a factor to a single-point estimate.

Subjective probability distributions can express technological uncertainty, but not requirements uncertainty. The number of routine calculations required by this technique makes extensive computer facilities mandatory.

The cost-estimating relation, a useful tool in cost estimation, is a statement of how one or more variables affect another. Even limited data can be used as empirical evidence in the derivation of cost-estimating relations. However, such data are often recorded by various organizations under many different and vaguely defined cost elements and must be rearranged so that like costs can be identified. The lack of data on existing missile and satellite systems reduces the effectiveness of using the cost-estimating relation in determining costs of future Air Force weapon systems.

Cost sensitivity analysis is best described as a systematic examination of the changes in total system cost as important system configuration characteristics are varied over their relevant ranges. This technique best provides

for requirements and technological uncertainties. In fact, it can even provide a range of cost estimates for a weapon system whose ultimate configuration is uncertain. Cost sensitivity analysis requires much more effort than a single-point estimate, but long or complicated cost-estimating procedures are unnecessary. This technique can be used readily by a small group of analysts without extensive computer facilities.

Other techniques, singly or in combination, may be useful in special situations. However, cost sensitivity analysis is the single most effective tool for estimating the costs of future weapon systems.



## TABLE OF CONTENTS

	<u>Page</u>
I. INTRODUCTION .....	1
II. DISCUSSION .....	5
A. Cost-Estimate Reliability .....	5
B. Analysis of Factors Influencing Cost Estimates .....	10
1. Technical Complexity .....	10
2. Technical Obsolescence .....	10
3. Schedule Slippages .....	11
4. Timing of Cost Estimate .....	11
5. Competitive Optimism .....	14
6. (This paragraph deleted from documents for open publication.)	
7. Inaccurate Cost Estimates .....	17
8. Price and Procurement Levels .....	17
9. Cost-Estimating Uncertainty .....	19
10. Air Force Requirements Uncertainty .....	19
11. Technological Uncertainty .....	21
12. Corroborating Studies .....	27
C. Evaluation of Cost-Estimating Techniques ....	31
1. Objective .....	31
2. Description of Available Techniques ....	32
D. The Most Satisfactory Technique—Cost Sensitivity Analysis .....	63
E. Application of Cost Sensitivity Analysis .....	69
1. Assumptions .....	69
2. Costs of Payload Weight and Basing Posture .....	70
3. Costs of Boosters and Propellants .....	74
4. Costs of Guidance System .....	74
F. Importance of Other Techniques .....	79
BIBLIOGRAPHY .....	83

## TABLE OF CONTENTS—Continued

### LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Correlation of Cost Overrun Factors with Time Slippage Failures .....	13
2	Correlation of Cost Overrun Factors with State-of-the-Art .....	26
3	Missile System Cost Sensitivity (Fixed Number of Missiles) .....	45
4	Satellite System Cost Sensitivity .....	46
5	Propellant Weight Factors .....	61
6	Missile System Cost Sensitivity (100 Missiles) .....	72
7	Time Phasing of Missile System Costs .....	77

### LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Development Cost Factor in Eleven Weapon Programs .....	6
2	Production Cost Factors in Twenty-Two Weapon Programs .....	7
3	Development Cost Factor Versus Development Time Factor .....	12
4	Production Cost Factors, Classified According to Degree of Technological Advance .....	23, 34
5	Development Cost Factor Versus State-of-the-Art Index .....	25
6	Weapon-System Cost Categories .....	39
7	Sensitivity of Cost to Payload Weight and Basing Posture .....	71

## A SURVEY OF TECHNIQUES FOR IMPROVING COST ESTIMATES OF FUTURE WEAPON SYSTEMS

### I. INTRODUCTION

Estimating the cost of future weapon systems is a difficult and uncertain process, but it is essential for budget preparation and for major program decisions. In choosing between possible military systems, costs of the alternatives must be estimated so that a logical selection may be made. The comparison of future weapon systems requires that data be gathered on the relative costs and effectivenesses of the systems.

A weapon system is defined by Air Force Regulation 80-1 (Reference 1) as follows:

"Weapon System. Composed of equipment, skills, and techniques the composite of which forms an instrument of combat, usually, but not necessarily, having an aerospace vehicle as its major operational element. The complete weapon system includes all related facilities, equipment, material, services, and personnel required for the operation of the system, so that the instrument of combat can be considered as a self-sufficient unit of striking power in its intended operational environment."

Improved cost estimates of weapon systems are becoming increasingly important because many of the new systems are

extremely costly and require a substantial portion of the Nation's resources. In addition, increasing numbers of systems are proposed for the same mission or objective.

Weapon-system cost analysis is much more than an estimate of the cost of the weapon itself. Weapon procurement costs may be relatively small compared to other necessary expenditures for base facilities, training of personnel, and operating expenses. Moreover, in the comparison and programing of systems for 5 to 10 years in the future, the costs of research and development must be taken into account. Recent experience indicates these costs are increasing in relation to other costs and may be expected to increase further as technological change accelerates. Therefore, the cost of the complete system must be estimated before alternatives can be compared. All related support costs for the entire life of the system must be included in the estimate. System life extends from the beginning of development, to system activation, and on through operation until the system leaves the active inventory.

This report reviews the inaccuracy of past estimates and evaluates methods for improving the cost estimates for weapon systems expected to become operational as much as

10 years in the future. The methods are studied to determine whether they:

- 1 Provide reliable and complete estimates
- 2 Constitute a means for rapid response to Air Force requests
- 3 Can be used by small groups of cost analysts without benefit of extensive computer facilities.

## II. DISCUSSION

### A. Cost-Estimate Reliability

Most weapon-system cost estimates made before procurement usually fall short of the actual amounts finally incurred. Sometimes the actual costs are many times the original estimates. Estimates made near the beginning of a development program are particularly unreliable.

Table 1 presents the ratio between actual and estimated development costs for 11 weapon programs (Reference 2: p. 22). Development costs include all the expenditures necessary to bring a weapon system to the point where it is ready for introduction into the operational force. These costs include amounts for research, test vehicles, ground-support equipment, and for all the activities associated with the test and evaluation of the weapon system. In the table, the average development cost factor is 3.2.\* Examination shows that development costs in the programs studied were as much as seven times the original estimates. In only one program were actual costs less.

---

\*All averages in this study are unweighted.

TABLE 1  
DEVELOPMENT COST FACTOR IN ELEVEN WEAPON PROGRAMS

<u>Program</u>	<u>Development Cost Factor*</u>
A .....	4.0
B .....	3.5
C .....	5.0
D .....	2.0
E .....	7.0
F .....	3.0
G .....	2.0
H .....	2.4
I .....	2.5
J .....	.7
K .....	<u>3.0</u>
AVERAGE .....	3.2

\*Actual cost divided by original cost estimate.

Table 2 summarizes some data on estimates of production costs (not including the cost of development) for 22 major Air Force weapon systems (Reference 3: pp. 467-469). Included in these 22 systems are fighters (F-84, F-89, F-100,

TABLE 2

## PRODUCTION COST FACTORS IN TWENTY-TWO WEAPON PROGRAMS

Fighters	Factor		Bombers	Factor		Carriers and Tankers	Factor		Missiles	Factor	
	Raw*	Adjusted**		Raw*	Adjusted**		Raw*	Adjusted**		Raw*	Adjusted**
1	5.6	3.9	1	8.7	5.1	1	1.7	1.5	1	57.6	10.5
2	3.6	2.5	2	3.5	2.8	2	1.6	1.5	2	20.7	7.7
3	3.1	2.0	3	1.5	1.1	3	1.0	1.0	3	11.1	3.6
4	2.1	1.5				4	1.0	.9	4	10.3	7.1
5	1.9	1.9							5	1.5	1.4
6	1.5	1.2							6	1.3	1.0
7	1.4	.9									
8	1.2	1.0									
9	1.2	.8									
Average	2.4	1.7		4.5	3.0		1.3	1.2		17.1	5.2

\*Raw Factor: actual cost divided by original cost estimate.

\*\*Adjusted Factor: adjusted actual cost divided by adjusted cost estimate.



F-102, and F-106), bombers (B-47, B-52, B-58), cargo and tanker aircraft (KC-135, C-133A), and missiles (BOMARC, SNARK, THOR, ATLAS, and TITAN). The ratio of the latest available estimate or actual cost to the original estimate is listed for each weapon system (e.g., if the latest cost estimate were twice the earliest available estimate, the factor would be 2.0). The average cumulative cost of production is the average cost of procurement of a given number of primary flight vehicles, and does not include the costs of research and development, other initial investments, and operation and maintenance. In Table 2, the average unadjusted cost factor is 6.5. The ratio between the latest estimate and the earliest estimate of the cost of production for these vehicles ranges from a minimum of 1 to a maximum of 57.6. If the extreme missile case, Number 1, is excluded, the average factor for the 21 remaining items is 4.1 instead of 6.5. There are substantial differences in the averages of the four classes of equipment. The average factor is 1.3 for cargo and tanker aircraft; for missiles it is 17.1.

The raw factors presented in Table 2 are unadjusted. Adjustments are made for changes in price levels or for differences between the actual number of vehicles procured

and the number of vehicles that were to be procured at the time the early cost estimates were made. Changes in price levels have generally been upward; therefore, the actual costs should be deflated. The cumulative average cost of production is a decreasing function of total output. Since actual total output usually is very different from the output which was originally anticipated, the original cost estimate, based on a different procurement level, is adjusted to reflect the actual number of vehicles procured.

As shown by Table 2, the effect of the adjustments is a reduction in the size of the factors. The average factor for all 22 items is reduced from 6.5 to 2.8. Most of the reduction is a result of the output adjustment rather than of the price-level adjustment. However, even after the adjustments were made on the raw factors in Table 2, the actual costs, on the average, exceeded the original estimates by 180 percent. Individual production costs were as much as 10.5 times the original cost estimates.

Tables 1 and 2 show that original cost estimates were 180 to 220 percent too low on the average, even after price-level and cost-quantity adjustments were made. For individual systems, actual development and production costs

were as much as 6 and 10 times greater than the early cost estimates. When cost estimates are in error by such large margins, the decision maker has difficulty in selecting logically between alternative weapon systems.

## B. Analysis of Factors Influencing Cost Estimates

### 1. Technical Complexity

One of the outstanding features of today's weapon-system programs is technical complexity. This technical complexity includes:

- 1 A large number of technical problems for each new weapon system
- 2 The interrelation among the technical problems
- 3 The large number of components in the system in light of reliability requirements.

All of these obstacles may be encountered within any one program.

### 2. Technical Obsolescence

Technical obsolescence is another problem of today's technical environment. Weapon-system programs must often be changed or canceled as the technical state-of-the-art advances. The SNARK system is an example. The SNARK program, begun in 1946, was for the development of an

air-breathing guided missile which would fly subsonically and have a range of 6,000 miles. By 1959, the less-vulnerable ballistic missiles had made SNARK obsolete. The program was terminated after an expenditure of about \$700 million and procurement of only one operational squadron. Similarly, the NAVAHO, an Air Force supersonic air-breathing missile costing about \$700 million, was made obsolete before it entered production by the development of the ballistic missile.

### 3. Schedule Slippages

Another possible cause of cost overruns in development programs is long development time. The data reviewed indicate that cost overruns decreased as greater emphasis was placed on minimizing development time. As can be seen in Table 3 and Figure 1, the greater the schedule slippage in a program, the larger the cost overrun (Reference 2: p. 442).

### 4. Timing of Cost Estimate

Another factor that should be considered is the timing of the cost estimate. Was the cost estimate made before, or some time during, the development program? As might be expected, data indicate that average cost overruns tend to

TABLE 3

## DEVELOPMENT COST FACTOR VERSUS DEVELOPMENT TIME FACTOR

<u>Program</u>	<u>Development Cost Factor*</u>	<u>Development Time Factor**</u>
A	4.0	1.0
B	3.5	2.3
C	5.0	1.9
D	2.0	NA
E	7.0	1.8
F	3.0	1.3
G	2.0	1.0
H	2.4	1.3
I	2.5	1.3
J	.7	1.0
K	3.0	1.4
AVERAGE	3.2	1.43

\*Actual cost divided by original cost estimate.

\*\*Actual time divided by original time estimate.

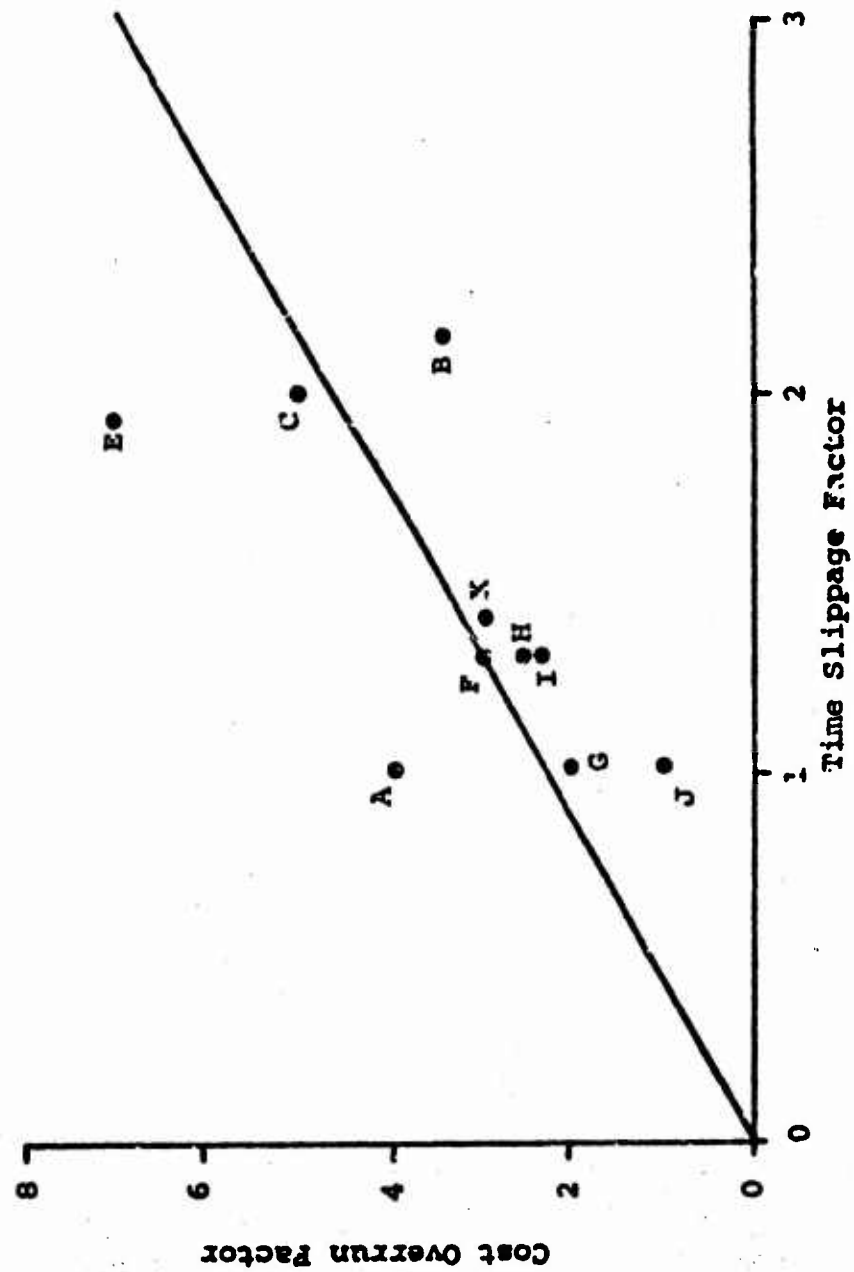


Figure 1. CORRELATION OF COST OVERRUN FACTORS WITH TIME SLIPPAGE FAILURES

decrease if cost estimates are made late in the development program. This study only considers cost estimates made early in the development program, because its purpose is to evaluate methods for estimating the cost of potential Air Force systems that could become operational 10 years in the future.

#### 5. Competitive Optimism

When a contractor learns of Air Force interest in a new concept, he prepares proposals which include cost estimates. The contractor usually reflects his desire to win the contract by outbidding the competition with optimistic cost estimates for initial development. However, not all of this optimism is due to the competitive strategy of the contractor. Sometimes the Air Force and its buying agencies discourage realistic cost estimates because the budget may be inadequate to support the new program. In other cases, Air Force requirements have placed a premium on achieving the maximum possible advance in state-of-the-art, thereby encouraging the contractor to prepare optimistic technical proposals. It seems impossible to separate the cost overrun caused by competitive optimism from that caused by technical uncertainty. Technical progress occurs between

the time the initial contractor estimates are made and when the program begins. However, there is little doubt that as the intensity of competition increases, the cost estimates in the contractor proposals become more optimistic.

The cost analyst is confronted with the task of making cost estimates of advanced systems with very little information other than the optimistic contractor cost estimates. He must somehow adjust these contractor estimates to take into account the competitive optimism of the contractor, if he intends to use the contractor's data. The better alternative would be for the cost analyst to make an independent cost estimate based upon the best available technical information and Air Force requirements for the weapon system.

6. (Paragraph 6 intentionally deleted from documents for open publication.)



#### 7. Inaccurate Cost Estimates

Another source of error in cost estimates can be the incompleteness of the cost analysis. Frequently, the cost analyst will produce poor cost estimates because he has failed to gather all the available technical and operational data on the proposed system. Many times, the estimate of total system costs does not include all the necessary elements of system costs. For example, the cost of a missile system might include the costs of the missile, the launcher, and the silo, but fail to include a prorated share of the cost of the launch control center. It is important that weapon-system costs be comprehensive, so that sound decisions can be made. It is equally important that all the assumptions on which the cost estimates are based be presented to the decision maker. Intrinsic errors may also be expected in the basic data used in cost analysis and in cost-estimating relations.

#### 8. Price and Procurement Levels

Changes in price levels during the development of a weapon system are relatively small sources of error, and cost estimates are usually presented in current dollar values. The crudeness of present cost estimates makes of

questionable value the added refinement of predicting price levels during the life of the weapon system. As a matter of general interest, it may be desirable to include the incremental costs caused by assuming several levels of inflation during the life of the weapon system. However, even if price-level changes could be forecast, the effect on the relative costs of alternative systems would generally be much less than that of other uncertainties. Such economic computations should be supplemental to the basic cost analysis.

The actual costs of any weapon system depend very much on the quantities procured. Large cost overruns are caused by cost estimates based upon one particular predicted force size or level of procurement. If for any reason a different number of items is procured, large errors in cost estimates result. A simple solution to this problem is the presentation of cost estimates for a wide range of procurement levels, thereby giving the decision maker the means for quickly and accurately determining the differences in total system costs as he changes the size of the force. Unit costs generally decrease as the quantity produced increases, and this functional relation is a necessary part of any cost analysis.

#### 9. Cost-Estimating Uncertainty

There are several possible sources of cost-estimating uncertainty. Cost-estimating relations used in cost analysis cannot be assumed to hold exactly. In estimating a certain cost component as a function of many variables, it cannot be assumed that the variables will predict the particular cost with certainty. The observations used in deriving cost-estimating relations invariably contain errors. In costing advanced Air Force systems, cost-estimating relations from past experience are sometimes used. Extrapolations beyond the range of the sample or data base from which the estimating relation was derived are another source of uncertainty. Cost-estimating errors may arise because of the use of techniques which involve a considerable amount of aggregation. An important cost element may be overlooked if the aggregations are large. Large aggregations also make cost comparisons of alternatives difficult.

#### 10. Air Force Requirements Uncertainty

Air Force requirements for a future weapon system drastically affect a development program and its associated costs. Sudden and unpredictable changes in technology,

enemy plans, and U.S. defense policies might require program redirection or even cancellation. Redesign of the weapon system might prove necessary and could produce a different configuration of the weapon system and all of its associated support equipment. The uncertainty is further compounded by the fact that the requirement for an advanced weapon is based upon intelligence estimates of the weapons possessed by a potential enemy. Intelligence estimates are subject to a considerable margin of error and change suddenly as new information becomes available.

Changes in the configuration of the weapon system are of two basic types. One change involves hardware characteristics. For example, a new engine may be included on a strategic bomber. The other involves the system's operational concept. For example, do the strategic bombers use existing Strategic Air Command bases? or are they dispersed to remote locations?

There are many possible reasons for changes in a system's configuration. The original design may fail to produce the required performance characteristics. Required performance characteristics may be changed with a resultant change in hardware specifications. An attempt may be made

to acquire the system sooner than was originally intended by substituting resources for time. The strategic situation may change, producing changes in system deployment. For example, a higher degree of dispersal or alert capability may be required to reduce vulnerability of the system to surprise attack in a new strategic situation. Such changes of operational concept could significantly affect installations and personnel costs which are substantial elements of total system cost. Of course, closely related to these possible reasons for changes in a system's configuration are the unforeseen technical difficulties that will be encountered in the development programs of future weapon systems.

#### 11. Technological Uncertainty

Technical problems of many kinds can be expected in a typical weapon-system program, and each of these unexpected difficulties has an effect on the contractor's ability to meet original time, quality, and cost predictions. Table 2 revealed a direct correlation between the average cost factors and different classes of equipment. The smallest average cost factor was computed for the cargo and tanker class and the largest for the missile class. The performance

requirements for new cargo and tanker aircraft are usually less than what has already been achieved by bomber aircraft. The engines for the cargo and tanker aircraft are usually "off-the-shelf" items. In terms of both performance and physical characteristics of the equipment, comparatively modest innovations are required in cargo and tanker developments. On the other hand, the technology which characterized the missile programs in Table 2 called for ambitious advances. Complex guidance and control systems and advanced propulsion techniques were required, and performance requirements were an order of magnitude greater than had been achieved before.

The correlation between degree of technical advance sought and cost overrun factors is demonstrated in Table 4 (Reference 3: p. 472). Technical experts classified the development programs in the table as small, medium, or large, according to the technical advance sought. The average cost factor shown is an increasing function of the size of the technical advance. Programs with small advances had an average factor of 1.4; programs with medium advances, 1.8; and programs with large advances, 4.2. However, there is some inconsistency in the cost factors of the individual

TABLE 4

PRODUCTION COST FACTORS, CLASSIFIED ACCORDING  
TO DEGREE OF TECHNOLOGICAL ADVANCE

<u>Small Advance</u>		<u>Medium Advance</u>		<u>Large Advance</u>	
Weapon Type*	Factor	Weapon Type*	Factor	Weapon Type*	Factor
C .....	1.5	B .....	2.8	B .....	1.2
F .....	1.8	F .....	2.5	F .....	1.0
C .....	.9	F .....	2.0	F .....	.9
C .....	1.5	F .....	1.2	B .....	5.1
C .....	.9	F .....	.8	M .....	1.0
F .....	1.5	M .....	1.3	M .....	10.5
				F .....	3.9
				M .....	3.6
				M .....	7.1
				M .....	7.1
AVERAGE 1.4		1.8		4.2	

\*B = bomber, C = cargo aircraft or tanker, F = fighter,  
and M = missile.

weapon systems. Several of the programs with small and medium technical advances had cost factors greater than several of the programs with large technical advances.

To further ascertain the extent of the correlation between technical advance and cost overrun factors, the development programs in Table 1 were assigned state-of-the-art indices as shown in Table 5. The state-of-the-art index measures the technical achievement and innovation required to accomplish the program's objective. The values of the indices range from 0 to 100. A development program with a 0 index indicates that no technical advance is required beyond the technology of systems already in production. An index of 100 represents a development program which would require significant and unforeseen breakthroughs in system technology. Programs with indices between 1 and 99 are within the state-of-the-art, and the magnitude of the index in these cases varies inversely with the amount of knowledge and experience available for each program.

Figure 2 presents data on the 11 development programs, with state-of-the-art indices plotted as the independent variable (Reference 2: p. 437). A positive correlation



TABLE 5

## DEVELOPMENT COST FACTOR VERSUS STATE-OF-THE-ART INDEX

<u>Program</u>	<u>Development Cost Factor*</u>	<u>State-of-the-Art Index</u>
A	4.0	90
B	3.5	65
C	5.0	92
D	2.0	55
E	7.0	90
F	3.0	80
G	2.0	50
H	2.4	85
I	2.5	60
J	.7	80
K	3.0	60
AVERAGE	3.2	

\*Actual cost divided by original cost estimate.

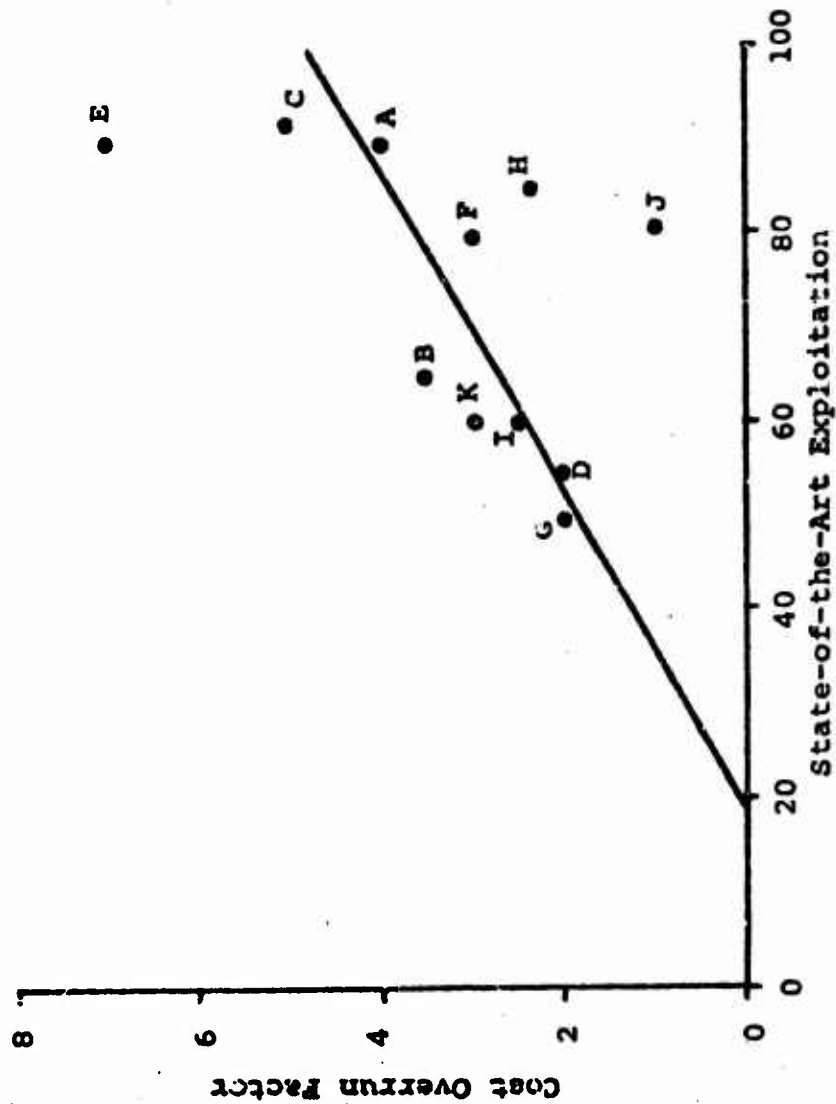


Figure 2. CORRELATION OF COST OVERRUN FACTORS WITH STATE-OF-THE-ART

was obtained between state-of-the-art exploitation and development cost factors, but the correlation coefficient is not high.

From the data shown in Tables 4 and 5 and in Figure 2, it seems reasonable to conclude that technological uncertainty is a major cause of production and development cost overruns.

## 12. Corroborating Studies

Study and analysis of historical cost data have indicated that requirements and technological uncertainties are the primary causes of errors in the cost estimates of future weapon systems. These uncertainties are so closely related that it would be unreasonable to consider them separately. Cost-estimating uncertainty caused by intrinsic errors in costing a fixed configuration is small in comparison with requirements and technological uncertainties. The conclusions of other studies support this statement.

One of the first works in this area was prepared by Eugene Brussell at The RAND Corporation (quoted in Reference 4: p. 7). He concluded that the primary cause of cost overruns is that the equipment being costed changed after the estimates were completed and that most of these

changes resulted in higher costs. However, Brussell was primarily concerned with systems hardware costs rather than total cost. Marshall and Meckling, after studying Brussell's work and Robert Summers' expansion of it, reached similar conclusions regarding the main source of error in cost analysis. They pointed out that early cost estimates for producing or developing something new are usually based on the initial design and program plans. As development proceeds, the initial designs and plans are almost invariably changed, either because of unforeseen technical difficulties or because the customer decides it is essential that the equipment be modified to keep pace with changing predictions of enemy capabilities, new operational concepts, and new technological possibilities.

In theory, it would be possible to divide into two parts the total error in cost estimates as they are prepared:

(1) errors in the cost of the configuration supplied by the cost estimator (i.e., the intrinsic error in cost-estimating), and (2) changes in the configuration as development progresses. In practice, it has not been possible to carry out this separation. However, in the costing of most major items of military equipment, the intrinsic errors

tend to be small in relation to errors caused by configuration changes (Reference 4: p. 8). Scherer and Peck concluded that one of the primary causes of cost overruns is the unexpected difficulty caused by technical uncertainties (Reference 2). Hitch and McKean agreed that technological uncertainty is the major source of error in cost estimates of future weapon systems (Reference 5: p. 189).

Another study considered variations in total system cost stemming from changes in system operational concept (Reference 4: pp. 8-9). The study pertained exclusively to intercontinental ballistic-missile systems. It provides data on more recent systems than does the Brussell study. The study concluded, as did Brussell, that the main source of variation in cost estimates is requirements uncertainty. It is apparent from the study that in 1954 to 1960, fluctuations in cost estimates were occasioned most frequently by changes in operational and organizational concept. In addition to examining variations in total system cost for ICBM systems, the study considered various components of the total. For example, estimates of personnel and training costs were shown to be clearly dependent upon varying concepts of combat employment for the ICBM force. Considerable

fluctuations in 5-year personnel and training cost estimates per operational missile have occurred as manning concepts have responded to changes in the salvo capabilities required.

Like the work of Brussell, this study presented cost variations in quantitative terms, but the explanations of the variations were mostly qualitative. Even though essentially qualitative, these explanations offer proof that most of the variations in system cost may be attributed to requirements uncertainty rather than cost-estimating uncertainty.

The question still remains as to the relative magnitudes of the two types of uncertainty. Attempts have been made to answer this question by examining case histories of past weapon systems, but the attempts were unsuccessful. The data sources available do not permit a quantitative identification of these two sources of error in cost estimates of weapon systems.

In another study, Armen Alchian examined several cases where requirements uncertainty was not a major factor (Reference 9: pp. 10-11). The study focused on items and methods of production that were well within the state-of-the-art. He was essentially examining cost-estimating

uncertainty. Although the data are neither recent nor very broad in scope, they do provide some basis for a quantitative statement on cost-estimating uncertainty. There is no reason to believe that the age or the amount of data preclude their validity. On the basis of these data, it is concluded that the variation in cost estimates attributable purely to cost-estimating uncertainty might average 20 to 30 percent. On the other hand, the works of Brussell, Summers, and others indicate that variation in cost estimates can average 200 percent or higher, while for individual systems, actual development and production costs were as much as 7 and 11 times the original cost estimates. If these data are accepted as reasonable, the conclusion is that variation in cost estimates attributable to cost-estimating uncertainty is small relative to that associated with requirements uncertainty.

### C. Evaluation of Cost-Estimating Techniques

#### 1. Objective

There is a need for a cost-estimating technique that will take into account technological and requirements uncertainties. The technique must be usable by a small group of cost analysts with technical backgrounds and very limited

data-processing equipment. It must require a minimum of calculations so that reliable cost estimates on future weapon systems and concepts can be provided to the Air Force on short notice.

## 2. Description of Available Techniques

### a. The Adjustment Factor

#### (1) Description

One possible solution to the problem of requirements and technological uncertainties in cost estimates is the use of adjustment factors. The adjustment factor is a cost overrun factor, defined earlier (Section II-A) as the ratio between the actual cost of the system and the estimated cost. The adjustment factor is applied to the cost estimate in an attempt to account for uncertainties in requirements and technology. The factor to be applied to the cost estimate would depend upon the kind of system being developed and the degree of technological advance associated with the system. On the average, the cost overrun factor increases as the technological advance increases. (See Figure 2, p. 26.) It is suggested that adjustment factors similar to the average cost overrun factors could be applied to cost estimates.



Engene Brussell is responsible for gathering the historical data on past weapon-system programs as shown in Table 2 (p. 7) and in Table 4 (repeated on p. 34 for convenience). In his analysis, he computed increases in major-equipment cost estimates by comparing estimates made early in a weapon-system program with estimates made late in the program. He concluded that the main benefits of his study were a clearer understanding of which systems are most likely to experience large cost biases, and some insight about the structure of the problem of uncertainty in cost analysis (Reference 4: p. 7). He indicated that it is not possible to develop adjustment factors which could be applied mechanically and which would be valid under a wide range of circumstances.

Brussell's study had some definite limitations. The analysis considered only major-equipment costs, not total system costs. The study was made when cost-estimating techniques, methods, and concepts were in their infancy. There is no way of determining who made the cost estimates or for what purpose.

TABLE 4

PRODUCTION COST FACTORS, CLASSIFIED ACCORDING  
TO DEGREE OF TECHNOLOGICAL ADVANCE

<u>Small Advance</u>		<u>Medium Advance</u>		<u>Large Advance</u>	
Weapon Type*	Factor	Weapon Type*	Factor	Weapon Type*	Factor
C .....	1.5	B .....	2.8	B .....	1.2
F .....	1.8	F .....	2.5	F .....	1.0
C .....	.9	F .....	2.0	F .....	.9
C .....	1.5	F .....	1.2	B .....	5.1
C .....	.9	F .....	.8	M .....	1.0
F .....	1.5	M .....	1.3	M .....	10.5
				F .....	3.9
				M .....	3.6
				M .....	7.1
				M .....	7.1
AVERAGE	1.4		1.8		4.2

\*B = bomber, C = cargo aircraft or tanker, F = fighter,  
and M = missile.

Care must be taken in interpreting the average factor increases. For example, in Table 4 the average production cost factor for a "medium" technological advance is 1.8. This is a simple average, and does not reflect the relative importance or type of weapon system. Four of the six entries in this column are fighters, one is a bomber, and one a missile. It is doubtful that this adjustment factor could be applied to a bomber or missile system with confidence.

Based upon further analysis of the data assembled by Brussell, Robert Summers developed a "magic formula" for deriving an adjustment factor for major-equipment cost estimates. Summers claimed that although the formula may not work very well in any one particular case, its repeated use for a large number of cases will result in equipment cost estimates which, on the average, will be more accurate than those obtained without the use of the formula. The important parameters which are included in the "magic formula" are:

- 1 The time the estimate is made in relation to the development program

-2 The degree of technological advance required

-3 The length of the development period.

When values of the above variables for a particular advanced system are substituted into the formula, the result is an adjustment factor. If, for example, the formula produces a value of 2.5 for a particular system whose major-equipment cost is estimated to be X, the adjusted estimate would be 2.5X. The formula, although complex, simply states that the adjustment factor for systems requiring only minor technological advances and short development time will be close to unity. But, when major technological advances are sought and development time is long, the adjustment factor will be greater than unity, probably between 2 and 3.

Certainly, it is not possible to correct a cost estimate perfectly by multiplying it by a factor which reflects the error of similar estimates in the past. However, if the estimates are not corrected, the data in Table 4 indicate that for a program requiring major technological advances, the cost estimate will be too low by an average factor of 4.2. Multiplication by a debiasing factor of 3 or 4 will not make the estimate

correct, but the revised estimate is likely to be closer to the actual costs than the original, unadjusted estimate.

Summers' analysis is a refinement of Bruscell's earlier work but is nonetheless subject to most of the same limitations. The data base is restricted with respect to both quantity and quality. The analysis is confined to major-equipment costs. The formula is complex and not easy to apply. Another problem arises from the probable difficulty of arriving at reasonable estimates for the degree of technological uncertainty to be substituted in the formula. Major-equipment cost is, in many cases, only a small part of the total system cost, which includes research, development, test, evaluation, initial investment, and operation of not only the primary vehicles, but also all the associated support equipment, facilities, and personnel. It is necessary to describe all of the cost elements of a weapon system so that the decision maker, faced with selecting a system from among several possibilities, will have the total cost, not just the procurement cost of the aircraft, satellite, or missile.

In order to prepare estimates of total system cost, the analyst should have a comprehensive list of the categories to be included. Table 6, an example of such a list, divides total cost into three major categories: research, development, test, and evaluation; initial investment; and annual operation. Subcategories are provided which outline total system cost in further detail. The list is intended to be as inclusive as possible to preclude the omission of significant elements of the total cost. The cost categories should be structured in such a way that those elements of the system which have the greatest impact on total cost can be easily determined.

There are advantages to a detailed listing of cost elements. First, the costs of individual elements of two competing weapon systems may be more accurately compared if both have been costed with the same format. Perhaps only major cost categories are available for a weapon system which is to be compared to another system. If the data for the other system have been divided into smaller elements, it might be possible to aggregate or recombine the small homogeneous units to match the

TABLE 6

WEAPON-SYSTEM COST CATEGORIES

Research, Development, Test, and Evaluation

Design and Development  
Test and Evaluation  
Management and Technical Direction

Initial Investment

Installations  
Primary Equipment  
Support Equipment  
Spares  
Initial Training  
Miscellaneous

Operation

Equipment Replacement and Maintenance  
Installations Maintenance  
Pay and Allowances  
Training  
Fuels, Lubricants, and Propellants  
Miscellaneous

major cost categories. By defining categories or subcategories to a reasonable degree, the cost analyst is less likely to overlook an important cost element.

If adjustment factors were applied only to the major-equipment category, many other important cost elements of the total system cost would be neglected. The following descriptions of the subcategories listed in Table 6 are intended to emphasize the scope of total system cost.

Under the major category of research, development, test, and evaluation, the design and development include preliminary design, applied research, mockups, test equipment, nonairborne instrumentation, additional plant facilities, and captive test operations. System test encompasses the costs of flight test vehicles, test operations, test ground-support equipment, and test facilities. Systems management and technical direction are usually performed by a corporation and include systems engineering and technical direction to contractors engaged in the development of the various subsystems.

Under the major category of investment, installations could include launch pads, runways, new



maintenance shops, and personnel facilities. The primary-equipment category is the aircraft or missile assigned to combat organizations. Support equipment could include launchers, control centers, cables, cranes, and trucks for a missile system. An allowance for spare parts and major-equipment spares is also assumed. Initial training costs cover the formal training of personnel and any line firings of missiles for training purposes. The miscellaneous investment category includes items such as transportation of initial supplies and equipment and the travel expenses of personnel to the operational bases.

Operating costs are recurring annual expenditures for operation and maintenance of the system once it has been initiated into service. Equipment replacement and maintenance is an important subcategory of operation cost. For example, significant replacement costs would be incurred for a certain number of satellites in orbit were required despite high attrition rates.

The cost of pay and allowances is determined by applying appropriate factors to the kinds and numbers of personnel required. The miscellaneous category includes transportation of replacement equipment and personnel.

If adjustment factors are to be used, they must be developed for all these elements of total system cost, not just the major-equipment category. There is practically no data base which could be used to derive the formulas. Even if such data existed, a different formula would be required for each cost element, resulting in a cumbersome and time-consuming technique. It would be extremely difficult to formulate cost elements having adequate flexibility for application to a wide variety of Air Force systems.

(2) Analysis

Adjustment factors can be applied to cost estimates to take into account technological uncertainties of a weapon system, but technical difficulties are only one part of the uncertainty problem. Technical breakthroughs, enemy capabilities, and new operational concepts cannot be accounted for by applying a factor to a single-point cost estimate. The estimate of the degree of technological uncertainty associated with a given weapon is at best fairly arbitrary, and to present only a single factor rather than a range of possible values is presumptuous.

Even if an adequate data base did exist for the derivation of adjustment factors for all the elements of total system cost, the technique would still be cumbersome, time consuming, and generally unsuitable for use by a small costing group.

b. Cost Sensitivity Analysis

(1) Description

Cost sensitivity analysis is the systematic examination of the changes in total system cost of a weapon system as important system configuration characteristics are varied over their relevant ranges. Configuration characteristics include hardware characteristics, system operational concepts, and the number of systems to be procured.

In systems analysis studies wherein alternative systems and different configurations of the systems are evaluated, cost sensitivity analyses are helpful in allowing for requirements and technological uncertainties. Cost sensitivity analysis can be used to establish the possible range of cost estimates for a future weapon system whose ultimate configuration characteristics are uncertain. The analysis should indicate which

particular configuration characteristics are relatively less sensitive to total system cost. This information is especially useful when total system cost is relatively insensitive to the most uncertain configuration characteristics.

Figure 3 presents sensitivities and insensitivities of various configurations of a hypothetical missile system. In the figure, the total system cost is shown to be relatively insensitive to increases in payload, possibly because many elements of total system cost, such as ground-support equipment and installations, do not change significantly as missile gross weight increases. However, the total system cost is sensitive to the type of propellant used in the missile. Solid propellants are less expensive to store and handle than cryogenic propellants.

Figure 4 illustrates a hypothetical satellite system's cost sensitivity to the probability of successful launch and to the length of time the satellite will remain in orbit. If the objective is to maintain a fixed number of satellites in orbit over a given length of time, total system costs would be very

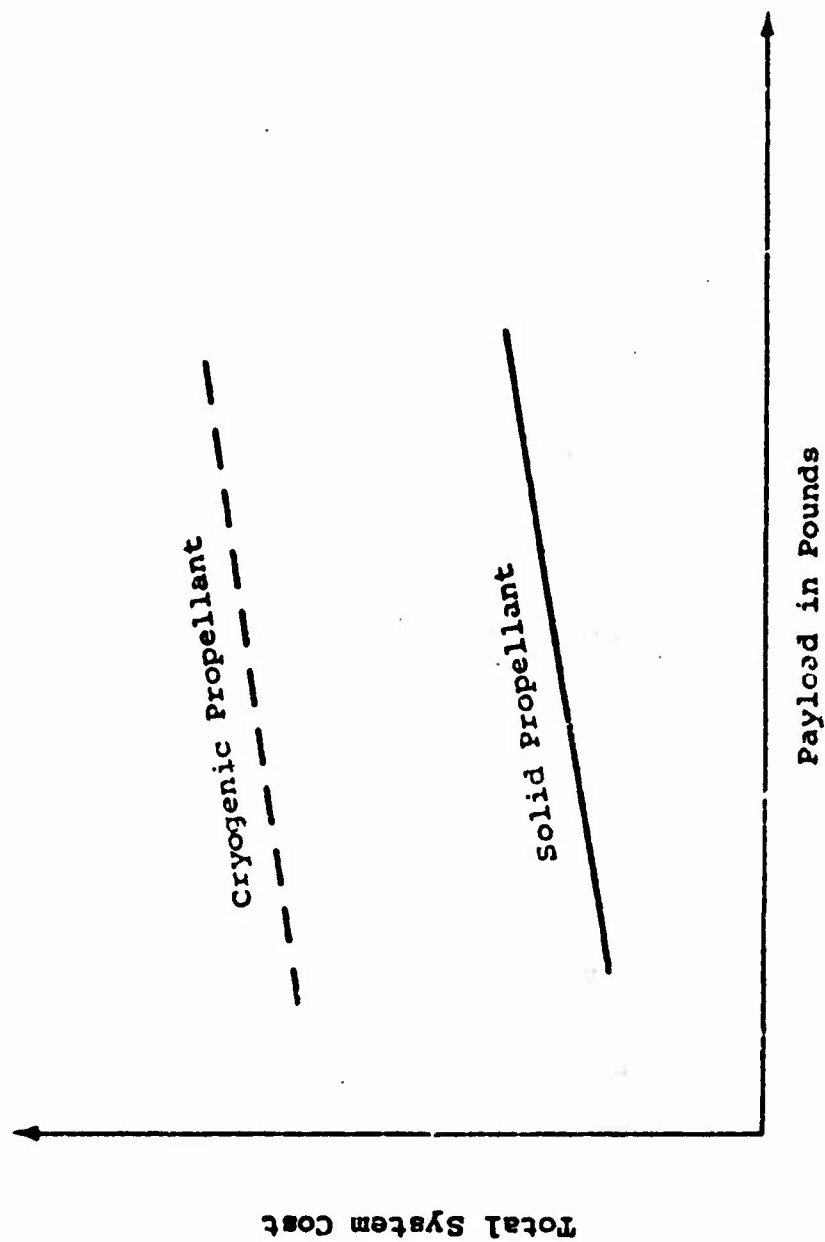


Figure 3. MISSILE SYSTEM COST SENSITIVITY  
(Fixed Number of Missiles)

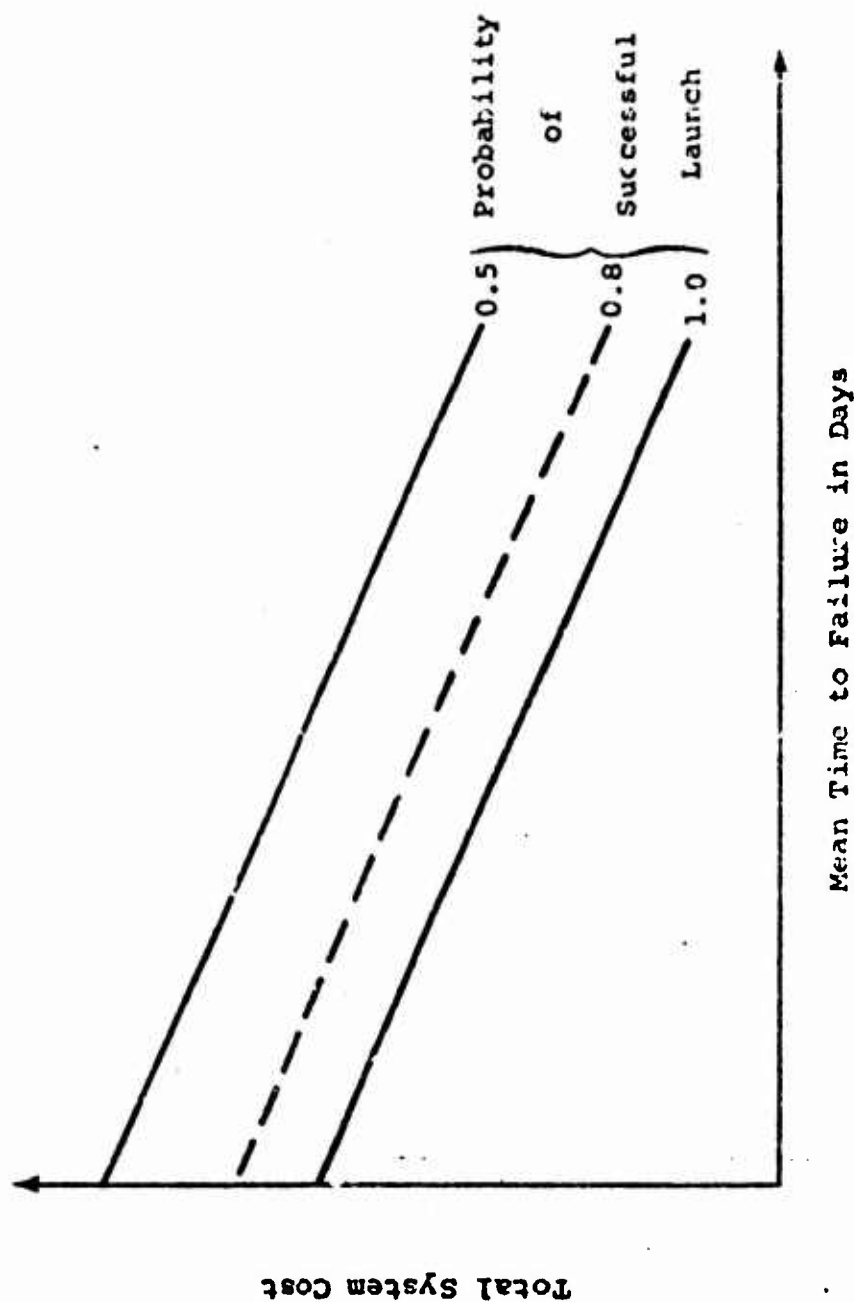


Figure 4. SATELLITE SYSTEM COST SENSITIVITY  
(Fixed Number of Satellites in Orbit)

sensitive to the launch reliability and mean-time-to-failure of the system. The sensitivity of various elements of the total system cost to launch reliability and mean-time-to-failure also could be shown in the same way.

(2) Analysis

Cost sensitivity analysis provides a range of system costs which is likely to be a more realistic guide than a single, most probable cost. However, there are limitations to consider. This technique requires much more work than does a single-point estimate. Sometimes it is difficult to present a concise and clear summary of all the numbers generated in an extensive sensitivity analysis. This is particularly true when the consumer of the cost estimates is not accustomed to applying the results of such an analysis. This technique does not furnish any formal measures of uncertainty as a basis for probability statements. Of course, there is no guarantee that any given cost analysis will include all the relevant ranges of characteristics or possibilities.

Although cost sensitivity analysis does provide a means to account for most of the elements of requirements uncertainty, it does not directly state the technological uncertainties of the weapon system nor the possibility of a change in enemy capabilities. On the other hand, it does account for such uncertainties indirectly by providing costs for a range of possible system characteristics. However, for any one of the many configurations analyzed, a certain technological advancement is decided upon as most likely representing the technical requirements for the system. Then, assuming that the operational requirements for the system do not change, the analysis would not indicate the increase in cost if unforeseen technical difficulties were encountered. If operational characteristics are compromised to avoid or lessen the effect of the technical difficulties encountered, the cost sensitivity analysis would provide cost estimates for the new configuration. For example, some unforeseen technical problems may arise in achieving the accuracy specified for the guidance system of an advanced missile system because of the weight limitations imposed on the guidance



package. More money may be spent to solve the technical problems that have prevented fulfillment of the performance requirements. Cost sensitivity analysis does not predict this unexpected expenditure. However, should the weight specified for the guidance package be increased to avoid large expenditures, cost sensitivity analysis would provide estimates for the new configuration. Moreover, if some technical breakthrough were achieved, cost estimates would be available for the new improved weapon system.

Certain characteristics of cost sensitivity analysis should be recognized. Usually, more time is needed to prepare a wide range of cost estimates than a single-point estimate. However, the likelihood that the single-point estimate will be reliable is extremely remote and, therefore, the additional time is well spent. Cost sensitivity analysis does not require any long or complicated cost-estimating procedures and can be used by a small group of cost analysts without computers.

In conclusion, cost sensitivity analysis does provide a technique which accounts for much of the requirements uncertainty by presenting a range of cost

estimates for many contingencies. It is considered one of the best available techniques for improving cost estimates of future weapon systems.

c. Subjective Probability Distributions

(1) Description

Another technique for expressing uncertainty in cost estimates allows the cost analyst to apply his feelings of uncertainty concerning total system costs. This technique does not show total cost uncertainty related to factors the analyst has neglected to consider or to changes in assumptions. It is useful for expressing the cost uncertainty remaining after the cost analyst has defined the system and identified assumptions as carefully as possible. The objective is to generate a quantitative statement about the range of reasonably likely values for total system cost. It is not recommended that a statement be made of only absolute upper and lower limits of the total system cost. Instead, subjective probability concepts should be used to describe information gathered by the analyst for each element of the total system cost. Uncertainty is quantified by defining a distribution reflecting the

relative probable values of all elements. Standard deviations for all system elements can then be computed and used to determine the standard deviation of the total system cost.

To apply this technique, it is first necessary to establish ground rules for the cost estimate, and then to use the best data and cost-estimating relations available. Next, the estimate is reviewed to identify the elements of the total cost which reflect various technical and operational uncertainties. Random variables are defined to represent the uncertain cost elements. The "subjective" distribution for each of the random variables is defined when a set of parameters for any of several distributions is specified. By using formulas associated with each representative distribution, the standard deviation and mean of each random variable is computed from the parameter values. Finally, with knowledge of how system cost elements were combined, the standard deviation and mean of the total system cost can be calculated.

The cost analyst probably would not like the task of computing a complete probability distribution to

indicate his feelings of uncertainty about each cost element. Therefore, unimodal distributions are recommended which the cost analyst can readily use by specifying only two or three parameters for each random variable. The greater the number of parameters that require specification, the greater the flexibility the analyst has in defining his feelings. For each cost element, the analyst should select that representative distribution which most closely resembles his impressions about the uncertainty.

For example, if the cost analyst chose a normal distribution, he could express his feelings by specifying the mode and the points which bind the central, 80-percent portion of the probability distribution. In a symmetric distribution, the mode is the mean, and both points must have the same deviation from the mode. The 80-percent range is arbitrarily selected as convenient for the cost analyst to attempt to specify. This procedure provides an idea of the standard deviation of the cost estimate. Other distributions that might be used are log normal, three- and four-parameter, linearly scaled Beta distributions, and trapezoidal

distribution. When sufficient quantitative empirical data are available, the standard deviation and mean may be computed directly without the use of representative distributions.

A simplified example of this technique is the determination of the cost of placing a number of satellites in orbit. Two independent variables are the cost of the booster and the cost of the satellite. A four-parameter, linearly scaled Beta distribution offers a wide variety of shapes that can represent uncertainty in cost estimates (Reference 7: pp. 1-11). The extreme limits, the mode, and the length of the central, 80-percent range are specified for each of the variables. If it is 80-percent probable that the actual cost will lie between \$60,000 and \$100,000, the length of the central range is \$40,000. The values expressed below are in millions of dollars.

<u>Variable</u>	<u>Extreme Limits</u>	<u>Mode</u>	<u>Central Range</u>
Booster	2.4 to 3.8	2.9	0.8
Satellite	0.05 to 0.5	0.2	0.1

The mean ( $\mu$ ) and the standard ( $\sigma$ ) deviation of the two cost elements are:

	<u><math>\mu</math></u>	<u><math>\sigma</math></u>
Booster	12.0	1.2
Satellite	6.5	1.3

Since it has been assumed that booster cost and satellite cost are not interdependent, the mean and standard deviation of the total cost are:

$$\mu_T = 12.0 + 6.5 = 18.5$$

$$\sigma_T = (1.2)^2 + (1.3)^2 = 1.77$$

If the total cost is normally distributed, the probability of an error in excess of \$1.77 million or one  $\sigma$  is 1/3. The probability of an error in excess of \$3.56 million (or about 19 percent of the mean) is 1/20. These values are the probabilities that a random variable is more than  $K\sigma$  away from the mean (Reference 7: p. 11).

The question is whether or not it is worth the effort to include a standard deviation for the total system cost. Additional information is required from

the analyst, and many additional steps are needed for the computation of the total system cost. The average cost analyst may be reluctant to select and use the distributions, and the number of routine calculations needed makes the use of a computer almost mandatory. Possible distributions and their characteristics would have to be readily available to the cost analyst. If uncertainty is not described statistically, the analyst requires far less information, but the results can be easily misused if uncertainty is not quantified. It is more realistic to quantify the uncertainty for each cost element than to do the same for total system cost, if the incremental time and funds required are available.

(2) Analysis

Subjective probability distributions are especially suited for expressing the technological uncertainty associated with the advanced weapon system. It is not clear how the technique could be used to express the uncertainties of enemy capabilities and changing operational concepts.

In applying this technique, the cost analyst is called upon to provide his estimates of the four

required parameters and to select a distribution that adequately reflects his feelings for the requirements uncertainty. Many additional steps are needed for the computation of the total system cost. Cost analysts with engineering backgrounds may not be receptive to a technique requiring the selection and use of probability distributions. Unless a computer is used, this technique would require too much time for a small group of analysts. The number of routine calculations involved makes the use of a computer almost mandatory for any size costing group.

d. Cost-Estimating Relations

(1) Description

Because historical cost data are scarce, standard statistical techniques can seldom be used in estimating the costs of future weapon systems. However, even limited data can be used as empirical evidence for the derivation of cost-estimating relations. A cost-estimating relation is merely a statement of how one or more variables affect another.



One of the biggest difficulties in gathering empirical data is that costs are recorded by various organizations under many different and vaguely defined cost elements. Available data must be arranged in such a manner that cost-estimating relations can be derived. Establishing a data base is a continuing job, and cost-estimating relations may change as more data are accumulated. The fundamentals of deriving cost-estimating relations are:

- 1 Identification of the variables
- 2 Establishment of the appropriate functional form
- 3 Recognition of the constraints
- 4 Determination of the confidence placed in the estimating relations.

Correlation and regression analyses are useful in evaluating these relations.

To demonstrate the use of this method, the costs will be estimated for development engineering and hardware fabrication of the airframe for a hypothetical advanced booster system. The THOR booster will be used

as the analog for the estimation. The design and development cost for THOR may be represented as:

$$C = 4.0X$$

where

- C = cost in millions of dollars
- 4.0 = THOR engineering time in millions of man-hours
- X = cost per engineering hour in dollars

The airframe for the hypothetical booster system is assumed to be different from the THOR booster in several respects. The new system is larger, has different propellants, and requires technological advancements. Each of these differences probably means an increase in the engineering hours required.

A scaling factor can be derived that takes into account the airframe requirements imposed by the chemical composition of the more advanced propellants. A scaling factor can also be used to adjust for the difference in weight. The ratio between the propellant weight of the new vehicle and that of THOR is a useful parameter, but cannot be used directly because the cost is not directly proportional to the weight of the

propellant carried. Instead, an estimate is made of the percent of this ratio which would adequately account for differences in the sizes of the two boosters. Such a relation is shown below, assuming no advance in the state-of-the-art:

$$C = 4.0X [Y(0.9 + 0.1 \frac{a}{b})]$$

where

- C = cost estimate in millions of dollars
- 4.0 = THOR engineering time in millions of man-hours
- X = cost per engineering hour in dollars
- Y = propellant factor (chemical composition)
- a = propellant weight of new booster
- b = propellant weight of THOR.

In the above relation, advances in the state-of-the-art have not been taken into account, except as reflected in the propellant factor which is a measure of the complications of using new combinations of fuels and oxidizers. For a given vehicle design, it is difficult to adjust for an advance in the state-of-the-art by manipulating the term in the relation which accounts for the difference in propellant weight. For example, the expression  $(0.9 + 0.1 a/b)$  might have been written

( $0.5 + 0.5 a/b$ ) if a significant advancement in technology were required. The selection of coefficients in this case is arbitrary (Reference 8: pp. 13-20).

The subjective reasoning that goes into accounting for advances in the state-of-the-art of airframes can be quantified by plotting a family of curves indicating propellant weight versus the ratios of airframe weight to various propellant weights. The curves shown in Figure 5 are based on the current state-of-the-art and on the assumption that a relatively minimum weight of tank, structure, and miscellaneous subsystem equipment exists for any given propellant weight. A proposed design using propellant A might have an airframe weight of 5,000 pounds and a propellant weight of 250,000 pounds, producing a ratio of 0.02. From the appropriate curve in Figure 5, it can be seen that the standard ratio of airframe weight to propellant weight is 0.03 for propellant A. The measure of complexity is the ratio of the proposed to the standard, or 0.03 to 0.02. This scaling factor of 1.5 could be included in the cost-estimating relation to reflect, at least partially, the increase in engineering man-hours

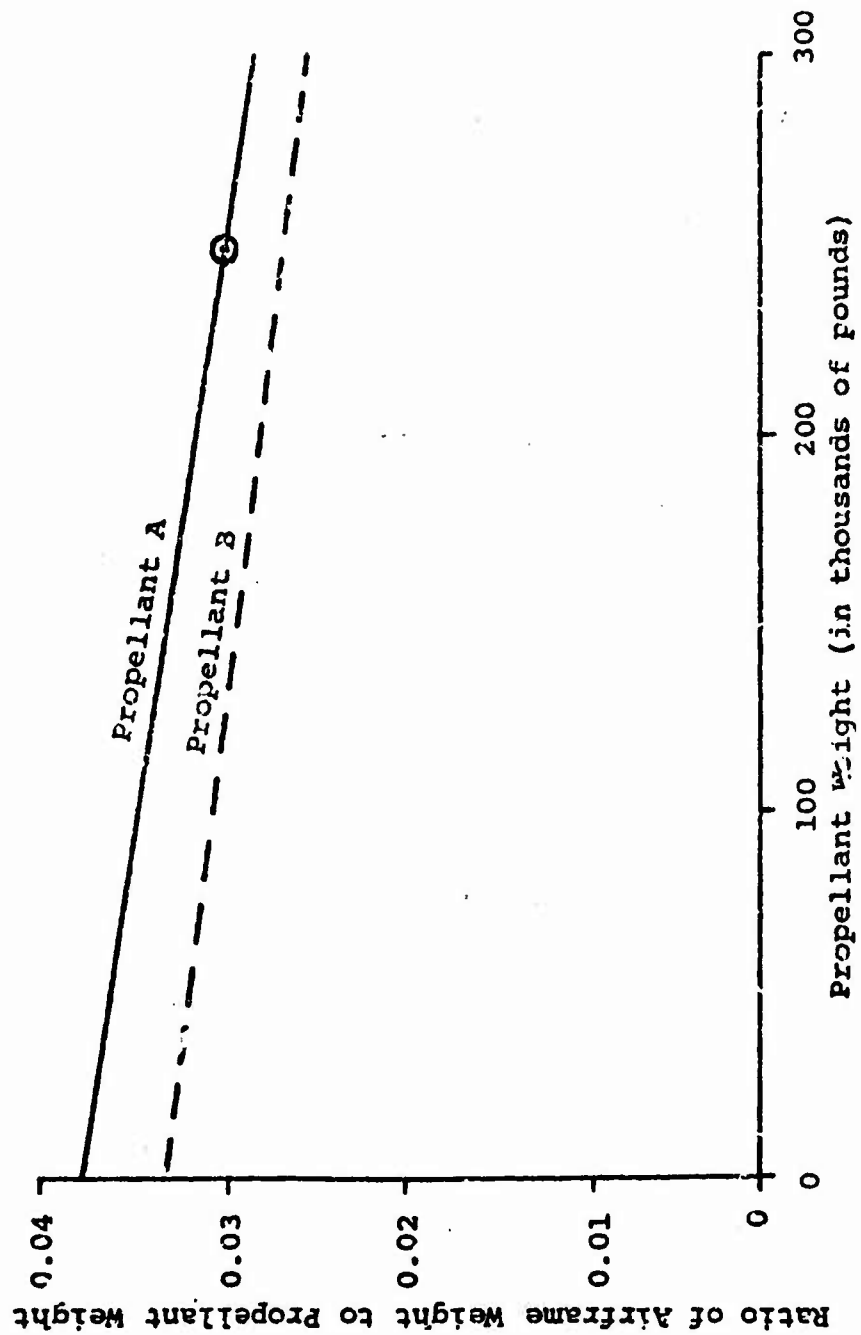


Figure 5. PROPELLANT WEIGHT FACTORS

necessary to achieve the structural weight factor for the proposed system. The lower the airframe weight for a given propellant weight, the more difficult the development.

The greatest disadvantages of techniques utilizing cost-estimating relations result from a general lack of an adequate data base from past, present, and projected programs. Some reasonably applicable data do exist for several aircraft programs, but little are available on missiles, and almost no data are available on satellite systems. In some cases, a simple factor relation may exist that can be expressed as a single number. For example, a factor for pay and allowances of personnel is readily available and easy to apply. On the other hand, estimating relations can be much more complicated and difficult to develop and apply quickly.

## (2) Analysis

Although certain terms in the cost-estimating relations may allow the cost analyst to apply scaling factors which could account for technological advancements required by the system, the cost-estimating relations in themselves do not state requirements

uncertainty. They can indirectly reflect uncertainty as the cost analyst interprets the available data before using the estimating relations. Some cost-estimating relations are simple to develop and apply; others are complex and involve lengthy calculations. A small group of cost analysts could easily apply many of the simple, well-established estimating relations, but it probably would not have the time nor the data to derive any new relations. Since the concern herein is Air Force systems planned for 8 to 10 years in the future, cost-estimating relations already in existence would probably not be useful.

D. The Most Satisfactory Technique—Cost Sensitivity Analysis

The technique most likely to improve cost estimates of future weapon systems is cost sensitivity analysis. Of the four techniques evaluated, cost sensitivity analysis best provides for requirements uncertainty. It can be used effectively by a small group of cost analysts and does not require extensive computer facilities.

One proponent points out that although cost sensitivity analysis was not developed initially to help cope with the

uncertainty problem per se, it can be useful in this regard (Reference 4: pp. 23-28). For example, it may aid in determining cost-estimating uncertainty. For this purpose, the requirements uncertainty would be assumed to be zero; then, the sensitivity analysis could be used to show how system cost varies because of uncertainties in cost-estimating relations, errors in basic data, extrapolation errors, and the like. This method could be used to solve an uncertainty about the price of a type of rocket propellant. The costs of future boosters which require the propellant could be estimated on the basis of several propellant prices, rather than on one. As a result, the sensitivity of total equipment cost to the probable range of propellant prices would be indicated.

No technique is perfect, and cost sensitivity analysis is no exception. It does not furnish any formal measures of uncertainty and thus does not provide the basis for probability statements. The many numbers generated in an extensive cost sensitivity analysis must be carefully presented to the group synthesizing the costs with the measures of effectiveness. Of even greater importance is the presentation of the cost-effectiveness analysis to the



Air Force decision maker. Here it is especially significant to indicate all of the possible contingencies associated with the cost analysis so that better decisions can be made.

Cost sensitivity analysis requires much more work than a single-point estimate, and there is no guarantee that all relevant possibilities will be included. Regardless of its limitations, cost sensitivity analysis is probably one of the best available techniques for dealing with the uncertainty problem in cost analysis of future systems and forces. It fits well with the over-all objectives of cost analysis, since the sensitivity approach is the one that is most useful to weapon-system analysis studies and other activities requiring cost inputs.

The cost sensitivity analysis approach applies equally well in a great many circumstances and at many decision levels. It is by no means limited to the defense field. In the automotive industry, cost sensitivity analyses are performed to guide the selection of designs for future transmissions and other automobile parts. This type of study is worthwhile in the automobile industry because of the high volume of the product which will be manufactured.

Cost sensitivity analysis is applied in electronics system design, where the implications of reliability, durability, or accuracy levels for a computer or radar set can be measured. It can be very useful in determining the cost implications of alternative designs for a particular component; for many people, this type of analysis is more important than the over-all sensitivity of the total costs to these design alternatives.

Cost sensitivity analysis is an attempt to estimate the financial magnitude of alternative weapon-system mixes, designs, and operational concepts, and the time phasing of these alternatives. Cost sensitivity analysis is not a complete study in and of itself, but is part of a full operations research or systems analysis effort. If it is to be useful, it must be integrated into the over-all cost-effectiveness evaluation.

Some critics of cost sensitivity analysis point out that the cost analyst specifies a likely range for each of the cost elements and then totals the lowest values and the highest values for all the cost elements to indicate a range of total system costs. In fact, the possibility is very remote that all elements will actually attain their lowest

or their highest values. Hence, such a range of values is an overstatement of the magnitude of likely variability in total system costs. However, this criticism applies to cost sensitivity analysis as it is used to cope with cost-estimating uncertainty, and does not detract from the usefulness of cost sensitivity in accounting for requirements uncertainty.

Another expert in the field of cost analysis of future weapon systems states that cost sensitivity analysis is a useful technique for dealing with problems of uncertainty, the more so because conventional statistical methods for deriving confidence limits and other measures of uncertainty cannot be applied to cost estimates (Reference 4: p. 20). First of all, to derive the conventional statistical measures of uncertainty, a representative sample must be drawn from a designated population and used as a basis for the statistical analysis. In the cost analysis of future systems, a large population is not available. On the rare occasions when samples can be drawn, the size of the sample is invariably very small, making the application of most statistical theory impossible. In studying proposed future systems, numerous uncertainties must be recognized together

with their impact on system costs. Studies of historical cost data have shown that perhaps the most important reason for differences between early estimates and final costs is that the ultimate configuration of the system was considerably different from that envisaged early in the program. Cost sensitivity analysis deals explicitly with cost differences related to differences in system configuration, and therefore can provide a range of system costs which is likely to be a more realistic guide than a single, most probably cost.

If extensive cost sensitivity analyses are required, the capacity of a small group of analysts may be exceeded. Therefore, it behooves the cost analyst and the Air Force to avoid broadening the scope of the analysis beyond that which is essential for making sound decisions.

However, there may be occasions when the importance and scope of the study necessitate the renting of computer time. Under these conditions, it would be important to reach an agreement with the consumer concerning the cost of the computer time as compared to the value of the analysis. Possibly the Air Force could arrange for free computer time, or could include such expenditures in the contractor's fee.

#### E. Application of Cost Sensitivity Analysis

The cost of a hypothetical advanced weapon system is analyzed in the following paragraphs to demonstrate the application and limitations of cost sensitivity analysis.

The Directorate of Development Plans, Headquarters United States Air Force, sends a formal request to a non-profit corporation for a cost-effectiveness study of a family of advanced ICBM's. The purpose of the study is to examine a wide range of payload weights that can be delivered by the missiles to determine which size of payload is the most cost effective.

##### 1. Assumptions

The following assumptions are made to simplify the analysis:

- 1 The booster system and corresponding propellants to be used are/well within the present state-of-the-art, and the same type of booster is used regardless of the size of the payload.
- 2 The same general type of re-entry vehicle is used for all payloads.
- 3 Two basing postures are considered--hard-fixed and truck-mobile.

-4 The guidance system is an advanced design and is well beyond current technology.

-5 A fixed number (100) of missiles is to be procured.

As a result of these assumptions, payload weight and the basing posture are variables, and all other elements of weapon-system design, development, and operation remain constant.

## 2. Costs of Payload Weight and Basing Posture

Table 7 is a sample format for displaying costs of many elements of the total system. Four payload weights are considered. System costs are prepared for the two basing postures for each payload weight. The major cost categories considered are research and development, initial investment, and 5 years of operation. The 5 years of operation is arbitrary, since weapon-system life can vary from 1 to 10 years. Usually, several system lifetimes are assumed, and the results are shown for the various assumptions.

A hypothetical set of results of the sample cost analysis is shown in Figure 6. Payload weight versus total system cost is plotted for the hard-fixed and truck-mobile basing postures. Probable cost limits are also indicated for the hard-fixed posture. The results indicate that

TABLE 7

## SENSITIVITY OF COST TO PAYLOAD WEIGHT AND BASING POSTURE

	Payload in Pounds					
	250		500		750	
	Hardened Site	Truck Mobile	Hardened Site	Truck Mobile	Hardened Site	Truck Mobile
Research and development Design and development Test and evaluation Subtotal						
Initial investment Installations Primary equipment Support equipment Training Spare Miscellaneous Subtotal						
Operation (5 years) Maintenance and attrition Pay and allowances Training Miscellaneous Subtotal						
TOTAL SYSTEM COST						

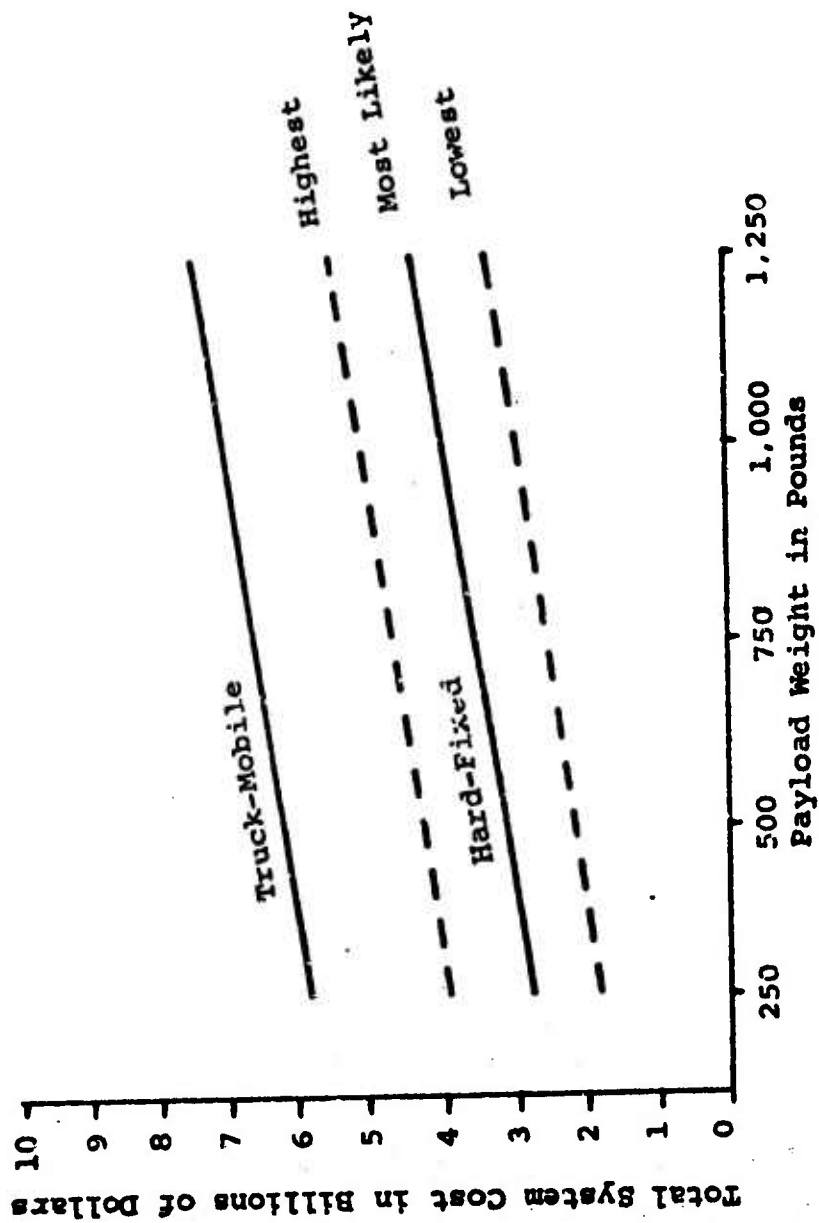


Figure 6. MISSILE SYSTEM COST SENSITIVITY  
(100 Missiles)



total system cost is fairly insensitive to the range of payload weights considered but is very sensitive to the type of basing employed by the missile. The development, procurement, and operation for 100 of the hard-fixed missiles for 5 years would cost a total of about \$2 billion. The truck-mobile system, with the same size payload, would cost about twice as much as the hard-fixed missile.

The kinds of information presented in a completed Table 7 and in Figure 6 are especially useful to the Air Force decision maker who is attempting to select the best weapon system from among several possibilities. For example, the decision maker who has a fixed number of dollars to procure the best weapon system can see immediately from the cost results that he can obtain roughly twice as many hard-fixed ICBM's as truck-mobile ICBM's. Then he can consider incremental advantages such as the increased survivability obtainable from a mobile system. Cost estimates developed from cost sensitivity analyses are readily adaptable to a variety of situations and can be meshed with the various measures of effectiveness.

Cost information, as presented in Figure 6, permits the user to assess quickly the cost implications of many of the

causes of requirements uncertainty. For example, if recent intelligence information indicated that the potential enemy had developed a means of destroying the hard-fixed ICBM's, the decision maker would have available cost data on an alternative basing posture, as shown. Improved ratios of warhead yield-to-weight might be achieved through underground nuclear testing. If warheads could be developed with higher yield for the same weight, a smaller missile payload weight would provide the same destructive potential. Again, Figure 6 indicates the possible cost saving of selecting a smaller payload ICBM.

### 3. Costs of Boosters and Propellants

The assumption was made that existing booster and propellant technology would be used for the missile system. Fairly accurate cost data should be available for items like those which have been developed and tested. Cost-estimating relations are probably available for determining the booster and propellant costs as a function of the weights required for the delivery of the payloads under consideration.

### 4. Costs of Guidance System

The guidance system to be used in the family of ICBM's is assumed to be an advanced design and is well beyond the

current technology. In this case, no historical data are available and cost-estimating relations have not been derived. The cost analyst is faced with the dilemma of costing a highly complex system that is described only in general terms and may even be impossible to develop. In Table 7, the cost of the guidance system is hidden in several of the subcategories of total system cost. For example, it accounts for some portion of the research, development, test, and evaluation costs, and, of course, the procurement costs of the primary equipment which, in this case, is the missile.

What can the cost analyst do to reflect his uncertainty about the development and procurement costs of the guidance system? One simple solution is to make a range of estimates based upon the best available information. The highest, lowest, and most likely costs of developing and procuring the advanced guidance system could be estimated. The next question to be answered is what effect does this range of estimates have on the total system cost? If the highest estimates for the guidance system have a negligible effect on total system cost, it probably would not be necessary to indicate the associated small increases in cost. However,

if total system cost is sensitive to the cost of the guidance system, the results should be presented to the decision maker.

It is difficult, if not impossible, for the cost analyst to prepare estimates covering such unexpected events as a guidance system's failing to meet system requirements or proving to be impossible to develop at any cost. One technique which accounts for such uncertainties is to estimate the rate of spending required to develop the system's components. This would indicate to the decision maker the amount of dollars already committed at the time when the feasibility of developing the advanced guidance system should be verified. Other useful information would be the cost of changing to an existing guidance system, should the advanced design prove impossible to develop. Figure 7 shows a typical time phasing of system costs for the major categories of research and development, investment, and operation. The point marked on the research and development curve indicates the anticipated date for determining the feasibility of developing the advanced guidance system. Should the system prove technically feasible, the solid lines indicate the most likely system costs for the

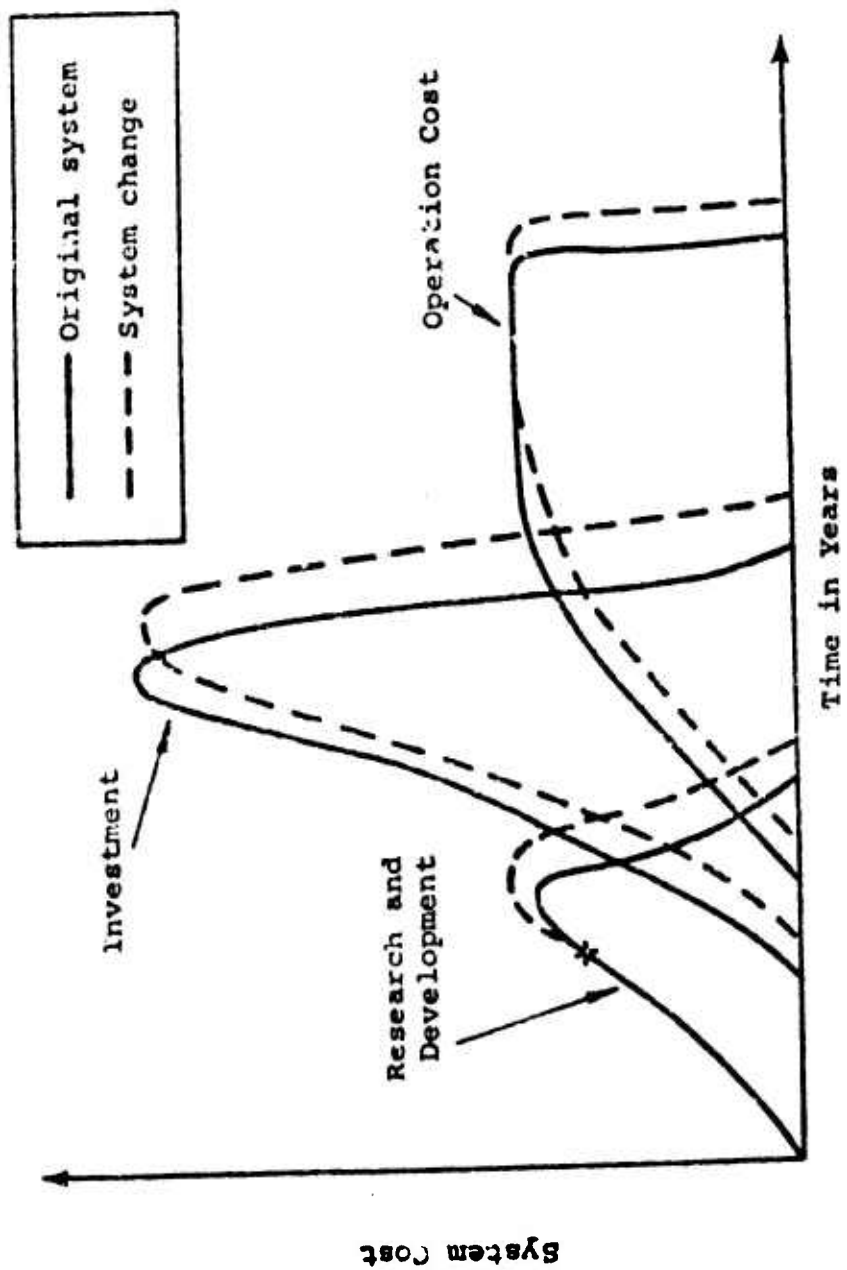


Figure 7. TIME PHASING OF MISSILE SYSTEM COSTS

remainder of the missile program. Should the guidance system prove to be impossible to develop, then the missile program might be revised to include a different guidance package. The dashed lines in Figure 7 show the effect on the system costs of switching to a different guidance system. Obviously, the money already spent on the advanced guidance system would be lost, and the effectiveness of the missile system probably reduced.

Unfortunately, past experience with weapon programs demonstrates that changes and delays in weapon-system development programs cannot be contended with this easily. For example, the estimated date for proving the feasibility of the new guidance system could slip. This might cause a series of costly delays in the rest of the program. After the guidance system proves feasible to develop, it may still fail to meet the operational requirements. This may lead to more costly delays and expensive modifications of the missile system. The cost analyst cannot anticipate such a wide range of possible events. However, by presenting good cost sensitivity analyses and by carefully outlining the assumptions behind the analyses, he can help the decision maker make more logical selections of weapon systems.

#### F. Importance of Other Techniques

The other three techniques discussed should not be disregarded. Adjustment factors, subjective probability distributions, and cost-estimating relations are all useful techniques in special situations. During the cost sensitivity analysis of a weapon system, one or more of the other techniques are almost certain to be helpful in estimating all the individual elements of total system cost.

There may be occasions when combinations of cost-estimating techniques might provide better estimates than cost sensitivity analysis alone. For example, the costing group may be asked to respond to a request from the Directorate of Development Plans in a matter of hours. On this occasion there would not be sufficient time to perform a cost sensitivity analysis. Instead, the costing group would probably supply the best single-point estimates that could be prepared in the allotted time. Probably a few contractor reports describing the system would be the only data available immediately. Perhaps one or two contractor reports might contain cost data. Usually, only the major categories of total system cost are shown in contractor reports, and it is difficult to determine which subcategories

are included in the costs. Many times the assumptions on which the cost estimates are based are incomplete or omitted. Since time would be insufficient to perform a cost sensitivity analysis, the cost analyst would have to apply some other technique. In this circumstance, the cost analyst should review the contractor costs for any obvious errors or omissions. Unless otherwise specified by the Directorate, the attempt should always be made to present total system costs. Next, the analyst should review past cost sensitivity analyses to find useful data on similar systems. Finally, existing cost-estimating relations and adjustment factors could be used to provide the quick single-point cost estimates. The limitations and assumptions that are an integral part of such rough estimates must be carefully explained to the user.

Cost sensitivity analysis does not provide any formal measures of uncertainty; therefore, it does not furnish the basis for making probability statements. If the Air Force requests this type of analysis, some other technique must be utilized. The PERT (Program Evaluation and Review Technique) is used to cope with uncertainty in schedule estimates. The PERT procedure assumes that the



distribution's standard deviation can always be approximated satisfactorily as one-sixth of the total range between the highest and the lowest estimates. However, standard deviations calculated in this manner may be unreliable, and no allowance is made for widely dispersed or sharply peaked distributions. Hence, the cost analyst's actual feelings might be distorted. To avoid some of these shortcomings, the subjective probability distribution technique described earlier is recommended. It should be kept in mind that the successful application of the subjective probability distribution technique depends upon a good background in statistics. In addition, automatic data processing is desirable.

There are many occasions when combinations of cost-estimating techniques offer better solutions than could be achieved with only one technique. For example, the cost of personnel pay and allowances is included in annual operating costs. Cost-estimating relations are well established for annual pay and support of the various grades of military personnel and serve as useful complements to the cost

sensitivity analysis. Other elements of total system cost could prove to be difficult to handle by cost sensitivity analysis. In such cases, adjustment factors and subjective probability distributions could be of help. However, cost sensitivity analysis is the single most effective technique for accurately estimating the cost of future weapon systems.

## BIBLIOGRAPHY

1. AFR 80-1, Research and Development, Definition of Terms (Department of the Air Force, Washington, August 1959).
2. Merton J. Peck and F. M. Scherer. The Weapons Acquisition Process: An Economic Analysis (Boston: Harvard University, 1962).
3. A. W. Marshall and W. H. Meckling. "Predictability of the Costs, Time, and Success of Development," The Rate and Direction of Inventive Activity: Economic and Social Factors, a report of the National Bureau of Economic Research, New York (Princeton, New Jersey: Princeton University Press, 1962, pp. 467-469).
4. G. H. Fisher. A Discussion of Uncertainty in Cost Analysis (RM-3071, The RAND Corporation, April 1962).
5. Charles J. Hitch and Roland N. McKean. The Economics of Defense in the Nuclear Age (R-346, The RAND Corporation, March 1960).
7. S. Sobel. A Computerized Technique to Express Uncertainty in Advanced System Cost Estimates (ESD-TR-65-79, The MITRE Corporation, September 1963).
8. J. W. Noah. Identifying and Estimating R&D Costs (RM-3067-PR, supplement, The RAND Corporation, May 1962).
9. A. Alchian. Reliability of Cost Estimates—Some Evidence (RM-481, The RAND Corporation, October 1950).